

Exploratory Analysis of Direction-Dependent Signal Propagation and Detection Under Real Constraints

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Abstract

This document provides an exploratory analysis of potential anisotropy in signal propagation as a companion to the proposed distributed precision timing experiment. The objective is to illustrate how directional dependence could manifest in timing measurements, examine scaling behavior across distance and direction, and outline detection strategies under realistic experimental constraints. No assumption is made that the model presented reflects physical reality.

1 Toy Model of Anisotropy

We adopt the illustrative model:

$$c(\theta) = c_0 (1 + \alpha \cos \theta)$$

where:

- c_0 is the standard isotropic speed of light
- α is a small dimensionless anisotropy parameter
- θ is the angle between signal propagation direction and the velocity $\vec{v}$ of the local frame relative to a possible preferred frame

2 Propagation Time Derivation

For a signal traveling distance L :

$$t(\theta) = \frac{L}{c(\theta)} = \frac{L}{c_0(1 + \alpha \cos \theta)}$$

For small α :

$$t(\theta) \approx \frac{L}{c_0}(1 - \alpha \cos \theta)$$

Let:

$$t_0 = \frac{L}{c_0}$$

Then:

$$t(\theta) \approx t_0(1 - \alpha \cos \theta)$$

3 Bidirectional Timing

Forward direction: θ

Reverse direction: $\pi - \theta$

$$\cos(\pi - \theta) = -\cos \theta$$

Thus:

$$t_f \approx t_0(1 - \alpha \cos \theta)$$

$$t_b \approx t_0(1 + \alpha \cos \theta)$$

Difference:

$$\Delta t \approx 2\alpha \cos \theta t_0$$

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4 Directional Sky Pattern

Because $\vec{v}$ is unknown, measurements correspond to arbitrary θ .

Key cases:

$$\theta = 0^\circ \Rightarrow \cos \theta = 1$$

$$\theta = 90^\circ \Rightarrow \cos \theta = 0$$

$$\theta = 180^\circ \Rightarrow \cos \theta = -1$$

This produces a dipole pattern:

$$\Delta t \propto \cos \theta$$

4.1 General Case

For arbitrary directions:

$$\Delta t_i \propto \alpha(\hat{n}_i \cdot \vec{v})$$

where $\hat{n}_i$ is the unit vector along propagation direction.

Thus the experiment effectively measures a dot product:

unknown $\vec{v}$ inferred from directional data

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5 Illustrative Numerical Example

Let:

$$\alpha = 2 \times 10^{-9}$$

$$\theta = 30^\circ \quad (\cos \theta \approx 0.866)$$

Then:

$$\epsilon = \alpha \cos \theta \approx 1.7 \times 10^{-9}$$

5.1 Earth–Mars

$$t_0 \sim 600 \text{ s}$$

$$\Delta t \approx 2\epsilon t_0 \approx 2 \times 1.7 \times 10^{-9} \times 600 \approx 2 \times 10^{-6} \text{ s}$$

5.2 Deep Space (Voyager scale)

$$t_0 \sim 8 \times 10^4 \text{ s}$$

$$\Delta t \approx 2\epsilon t_0 \approx 3 \times 10^{-4} \text{ s}$$

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6 Detection Under Real Constraints

Existing constraints imply:

- large anisotropy is unlikely
- detectable effects must be small or structured

Thus detection requires:

- long baselines
- multiple directions
- high-precision timing

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7 System Architecture

7.1 Local Constellation

Heliocentric spacecraft with similar orbital parameters:

- Earth-based clocks
- Lagrange-point spacecraft
- additional heliocentric spacecraft spaced $\sim 120^\circ$

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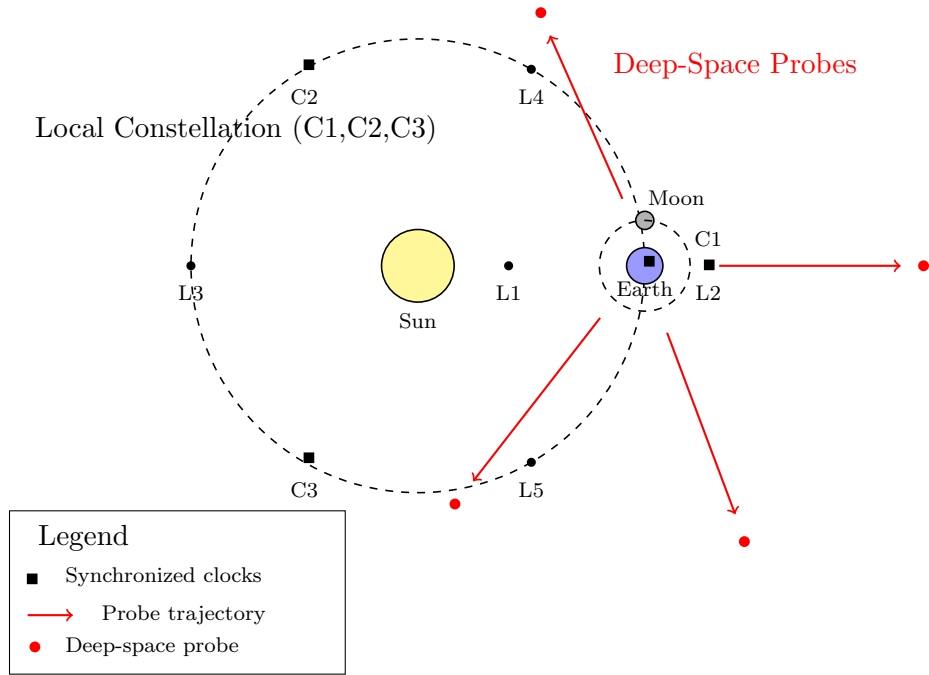
7.2 Deep-Space Probes

Non-coplanar trajectories:

- tetrahedron (4 probes)
- octahedron (6 probes)

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8 System Geometry Diagram



9 Measurement Strategy

Detection requires:

- sampling multiple directions
- reconstructing $\vec{v}$
- distinguishing propagation from clock effects

10 Conclusion

This analysis shows that even very small anisotropies could produce measurable effects over sufficiently large distances.

A distributed, multi-directional timing experiment provides a direct and controlled method for detecting such effects under realistic constraints.